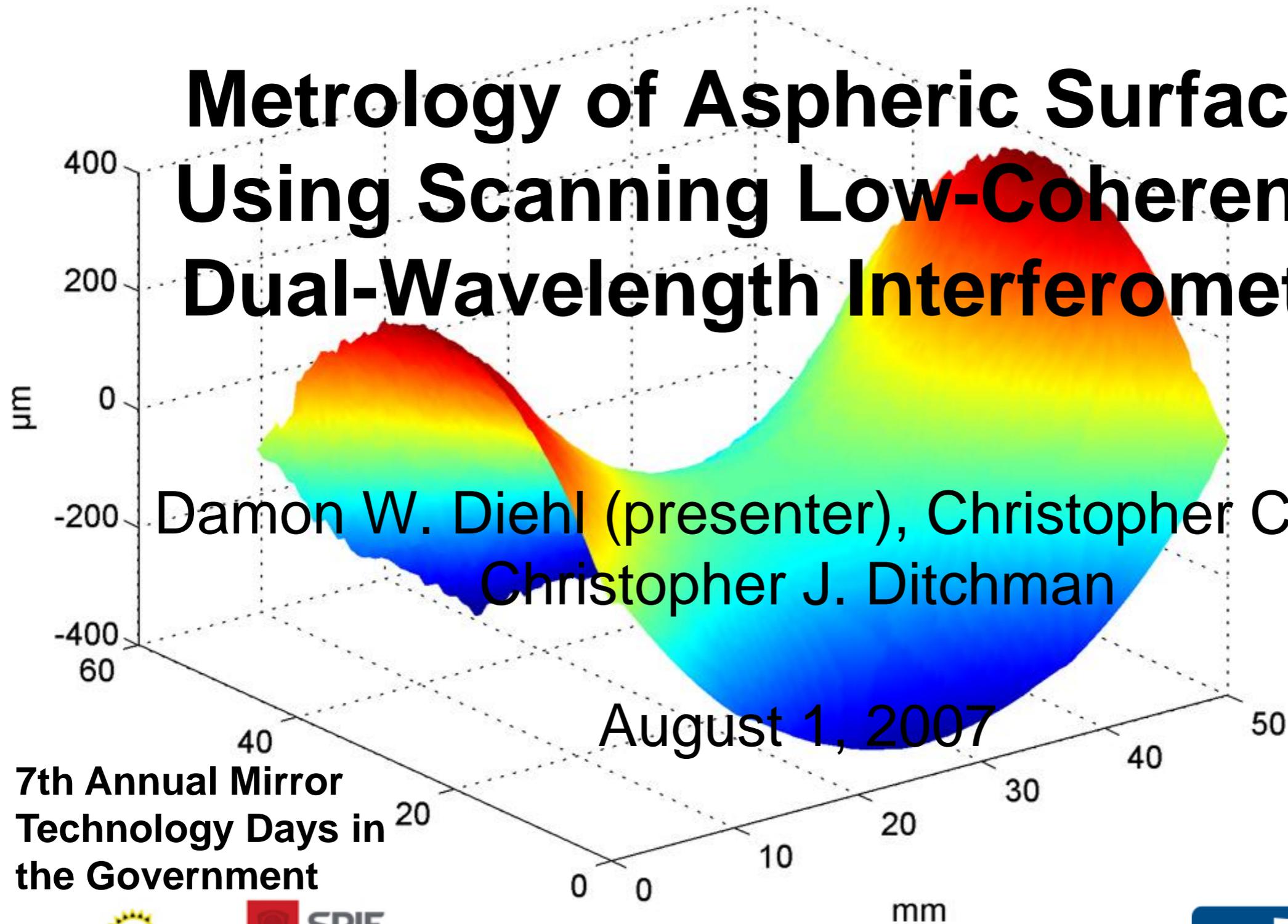


Metrology of Aspheric Surfaces Using Scanning Low-Coherence Dual-Wavelength Interferometry



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August 1, 2007

7th Annual Mirror
Technology Days in
the Government



Acknowledgements

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- A portion of this project was funded by US Army grant W31P4Q-06-C-0185.
- Lumetrics, Inc. provided the OptiGauge dual interferometer used for these measurements.
- Douglas Jacobs-Perkins and Steve Jacobs at the University of Rochester Laboratory for Laser Energetics provided metrology samples.

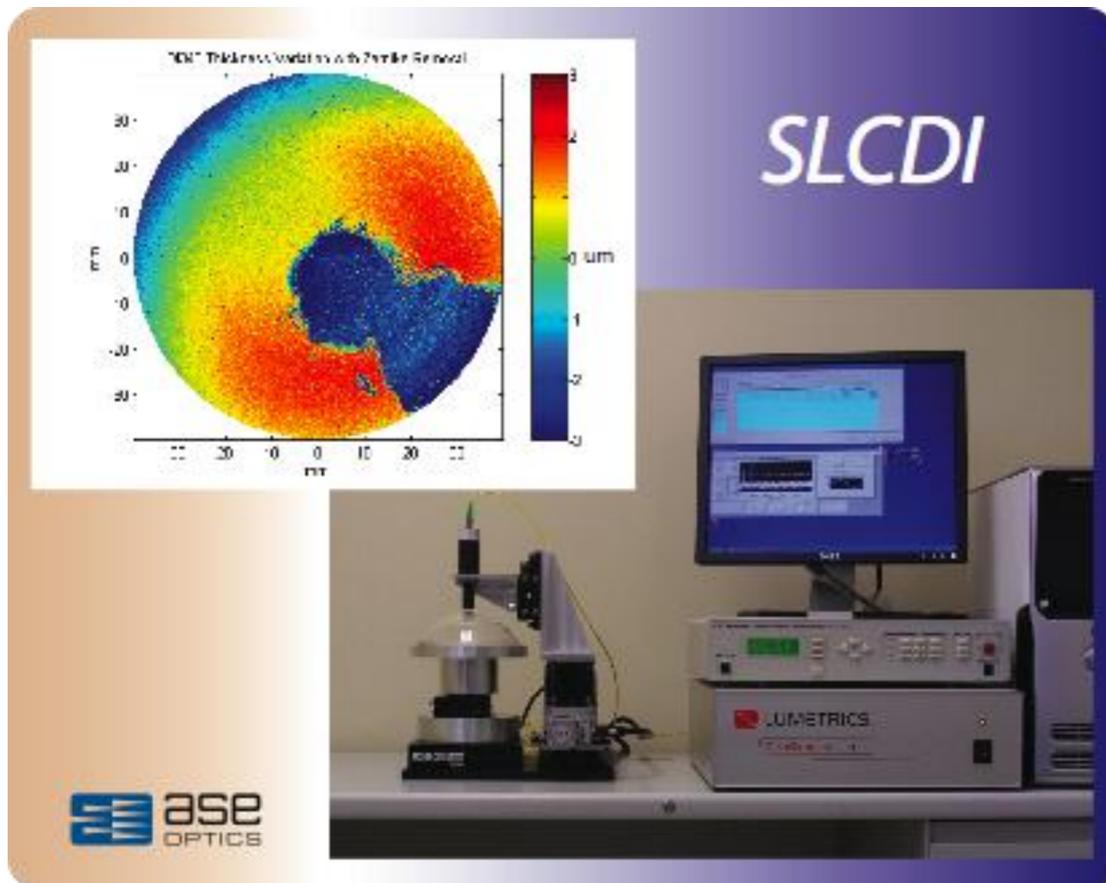
“The Big Picture”

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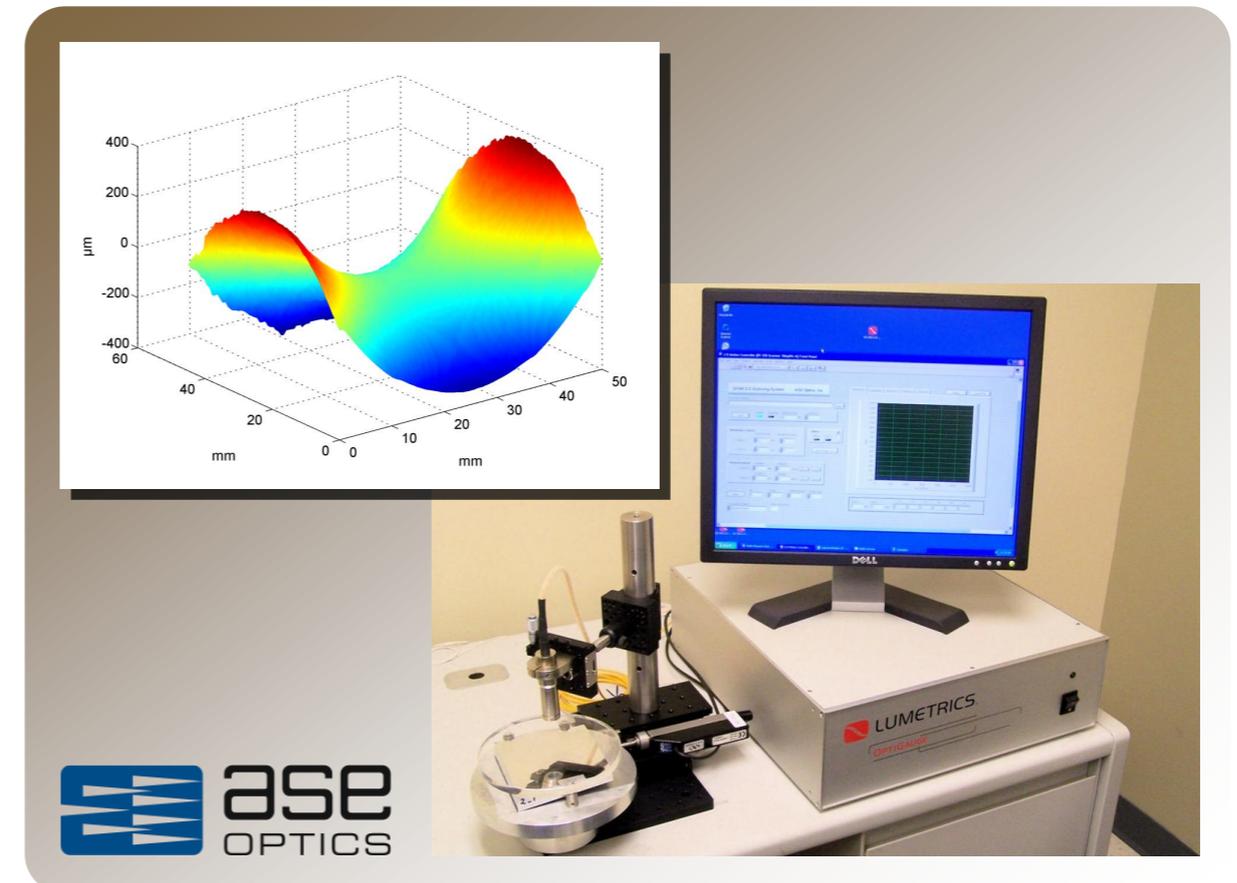


ASE Optics has developed a surface and thickness metrology instrument based upon scanning low-coherence dual-wavelength interferometry (SLCDI).

Thickness Metrology



Surface Metrology



Outline

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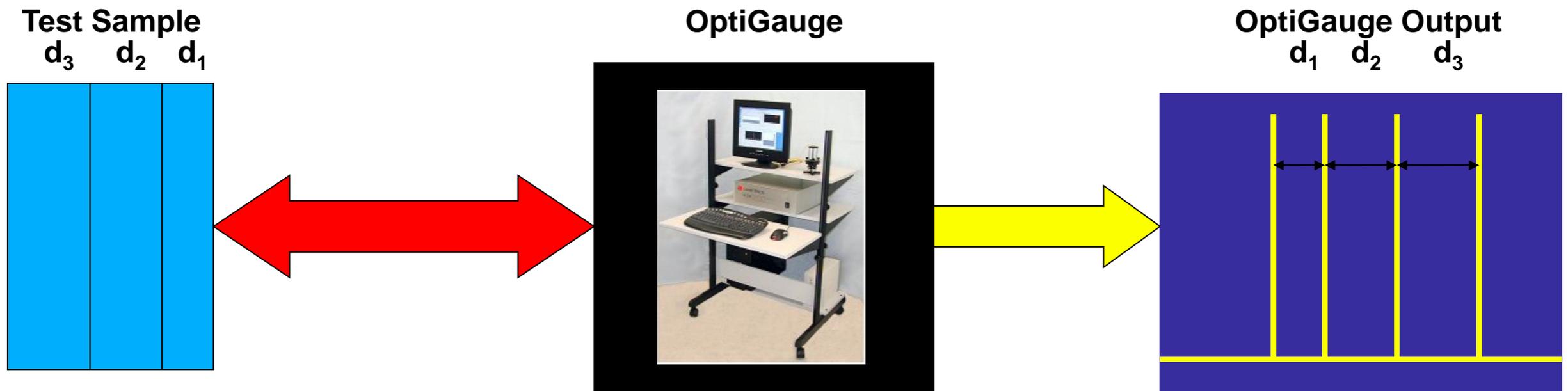
- **Lumetrics DI Overview**
- **Hemispheric dome scanning (Army SBIR)**
- **Aspheric surface scanning (independent research)**

“Black Box” Concept

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The OptiGauge uses low-coherence interferometry to simultaneously measure the thickness of each layer within a multilayer material.



- Minimum resolution: 100 nm
- Minimum optical thickness: 12 μm
- Maximum optical thickness: 12 mm

Kodak	<i>Proc. SPIE 3538, 180–191 (1999)</i> <i>Proc. SPIE 3538, 192–203 (1999)</i> <i>Proc. SPIE 4204, 61–70 (2001)</i> <i>Proc. SPIE 4578, 136–144 (2002)</i> <i>Proc. SPIE 5272, 150–156 (2003)</i>
LUMETRICS	<i>Proc. SPIE 5879, 23–41 (2005)</i>
ase OPTICS	<i>Proc. SPIE 6545 (2007)</i>

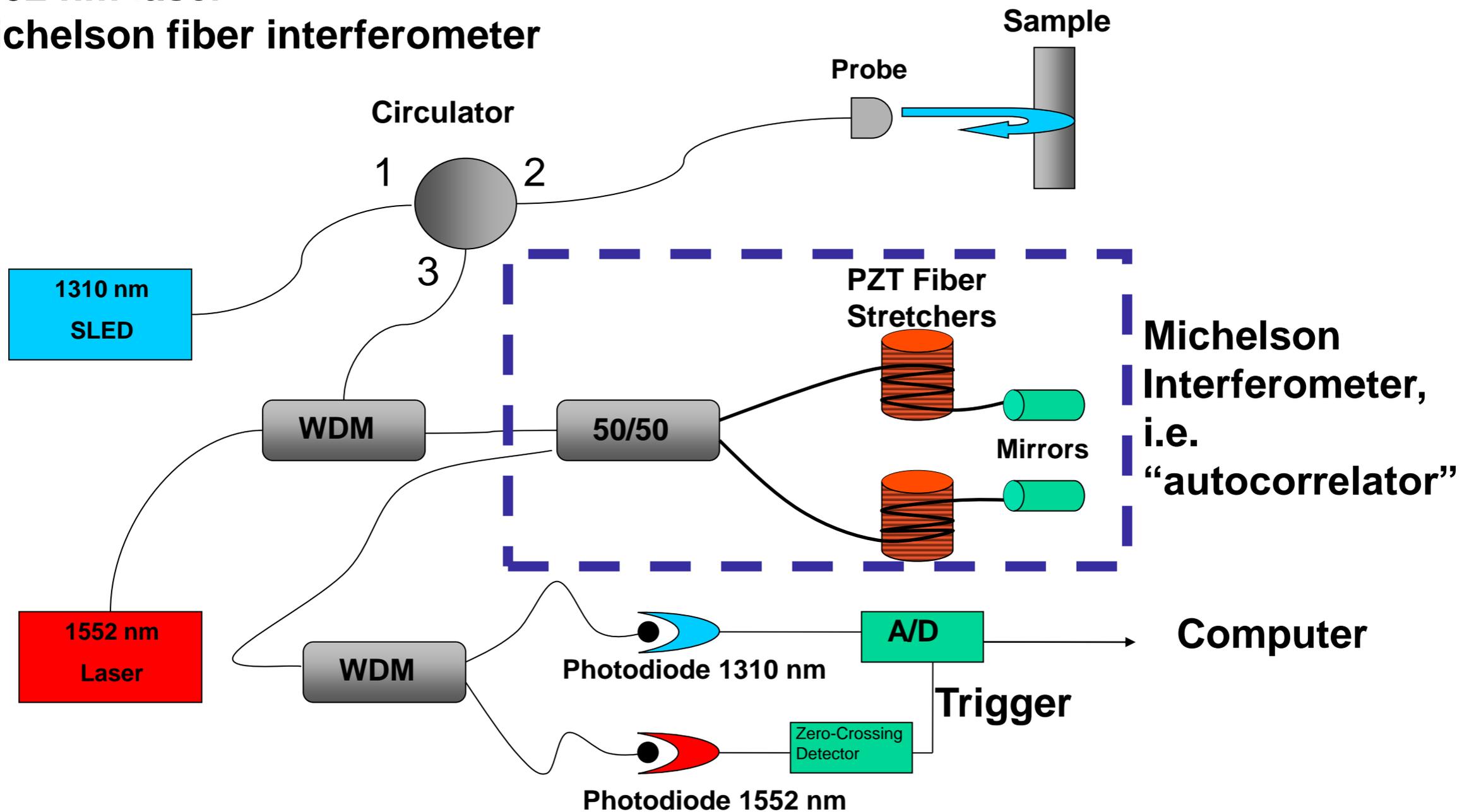
Insided the “Black Box”

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The key components inside the OptiGauge are:

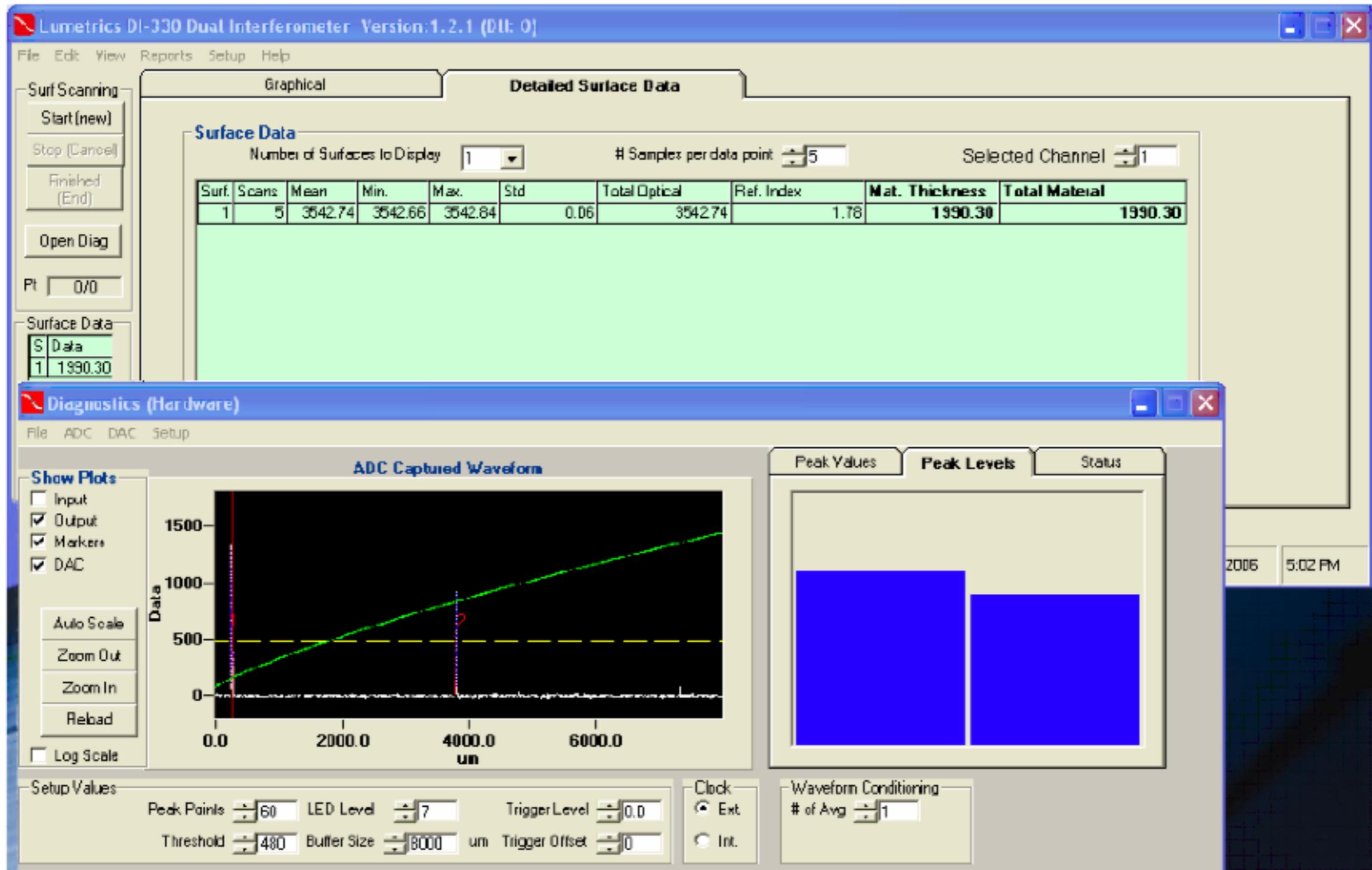
- 1310 nm SLED
- 1552 nm laser
- Michelson fiber interferometer



Lumetrics DI Overview:

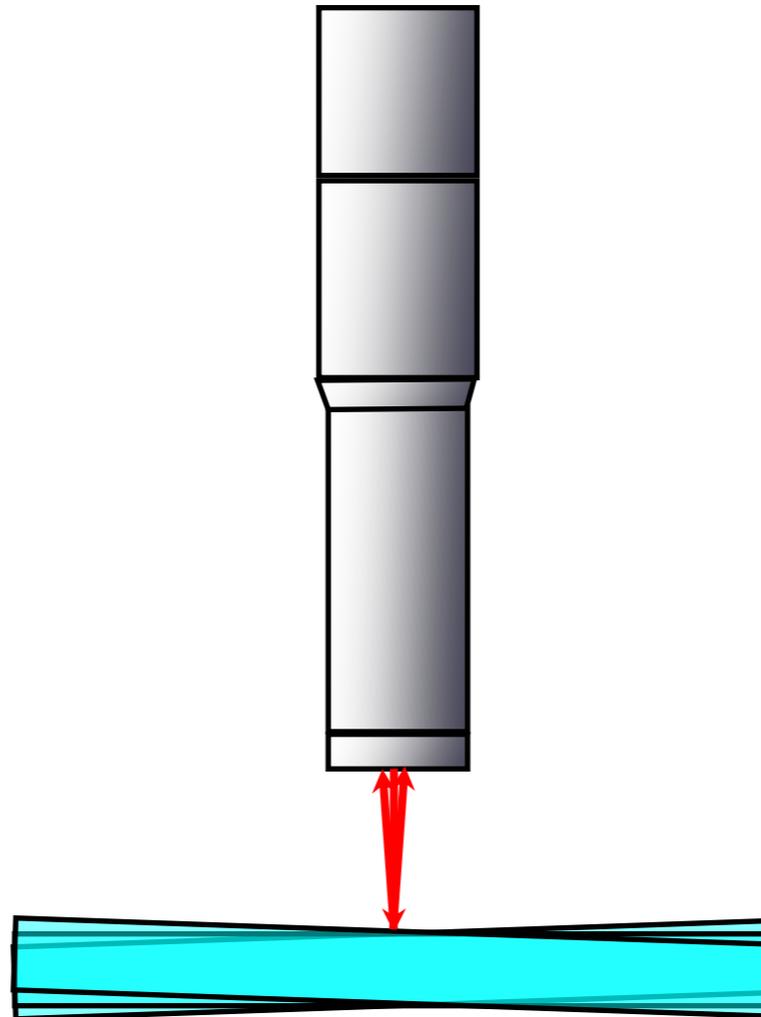
The OptiGauge DI 340 incorporates the data analysis into a simple graphic user interface.

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The OptiGauge probe can tolerate a $\pm 2^\circ$ surface deviation from normal.

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This tolerance allows the system to measure objects that differ significantly from planar or spherical without requiring complex conformal tracing.

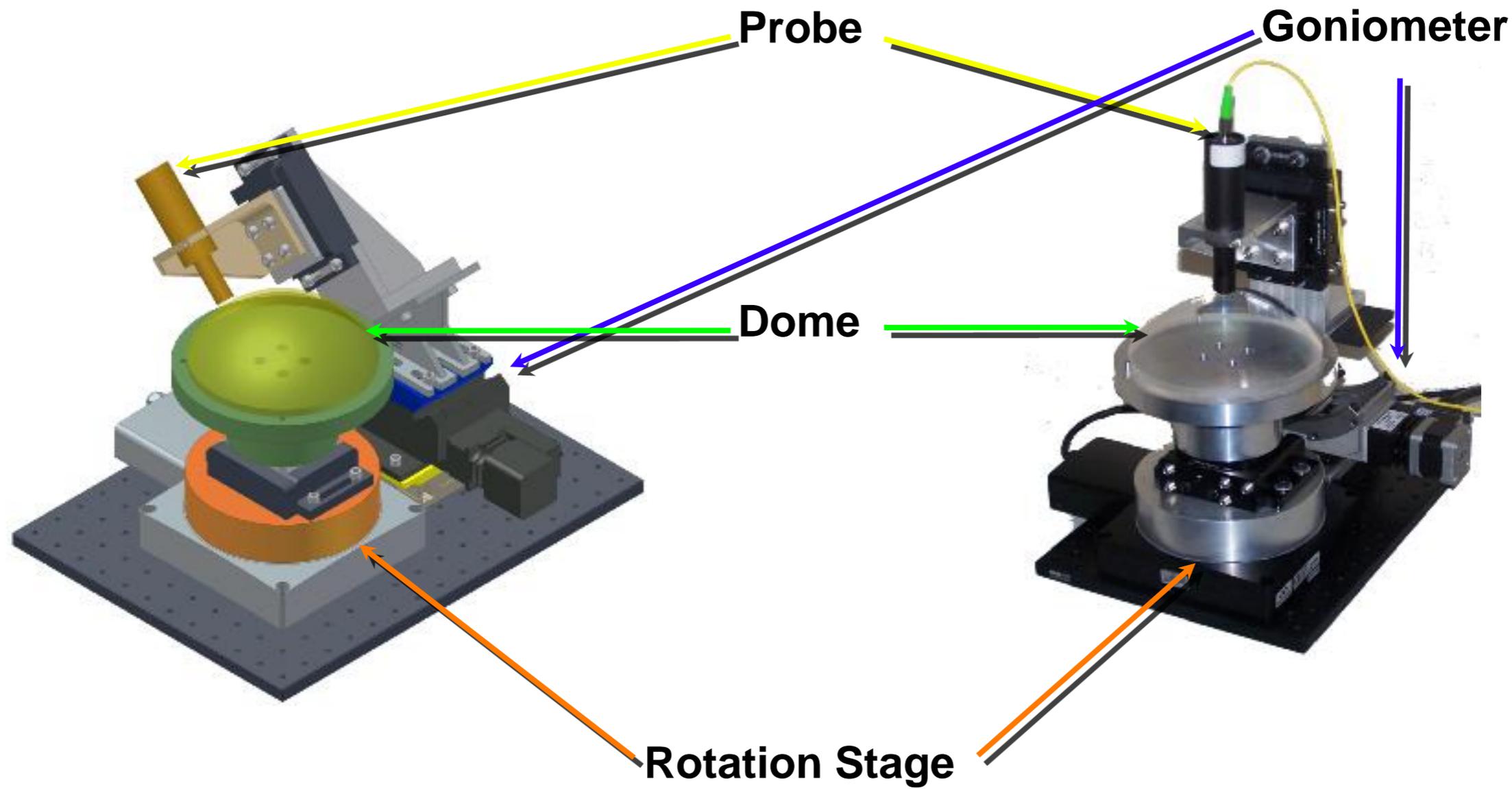
Outline

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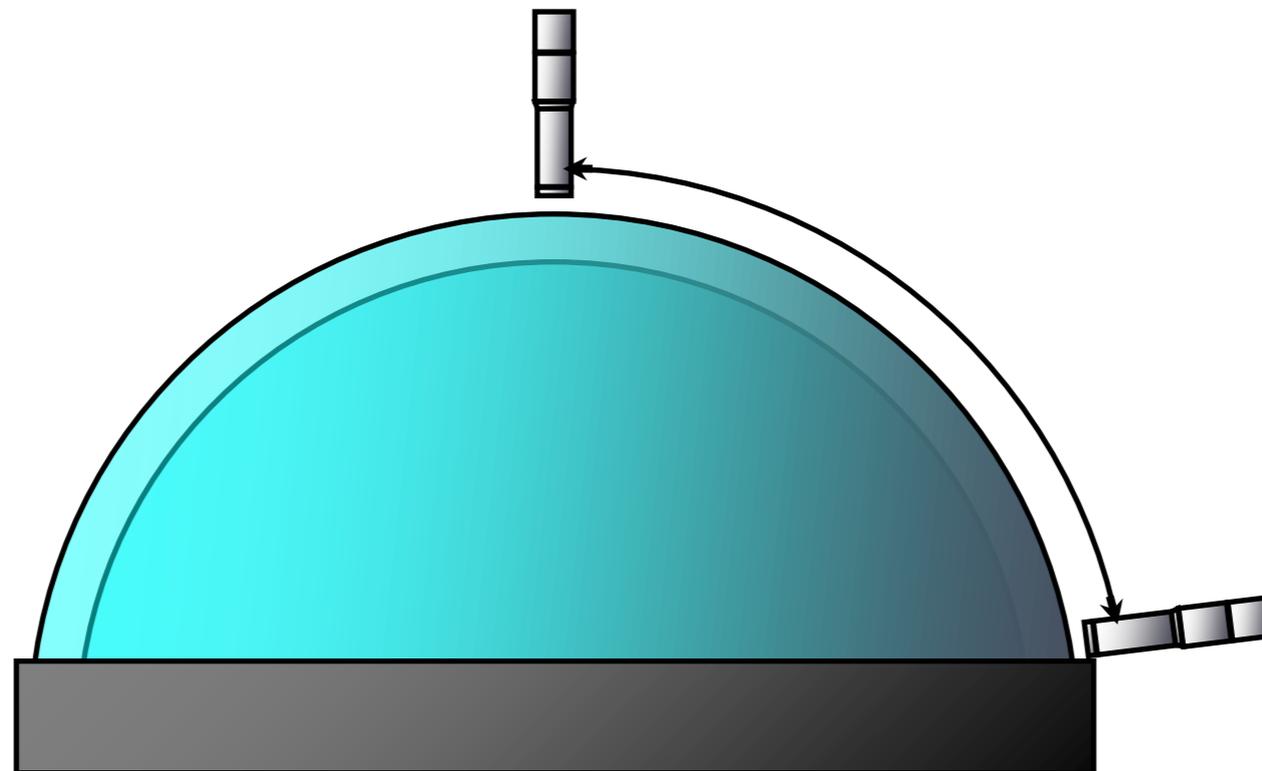
- Lumetrics DI Overview
- **Hemispheric dome scanning (Army SBIR)**
- **Aspheric surface scanning (independent research)**

Scanner Components



The rotation stage and goniometer allow us to scan the dome surface conformally with the probe at normal incidence.

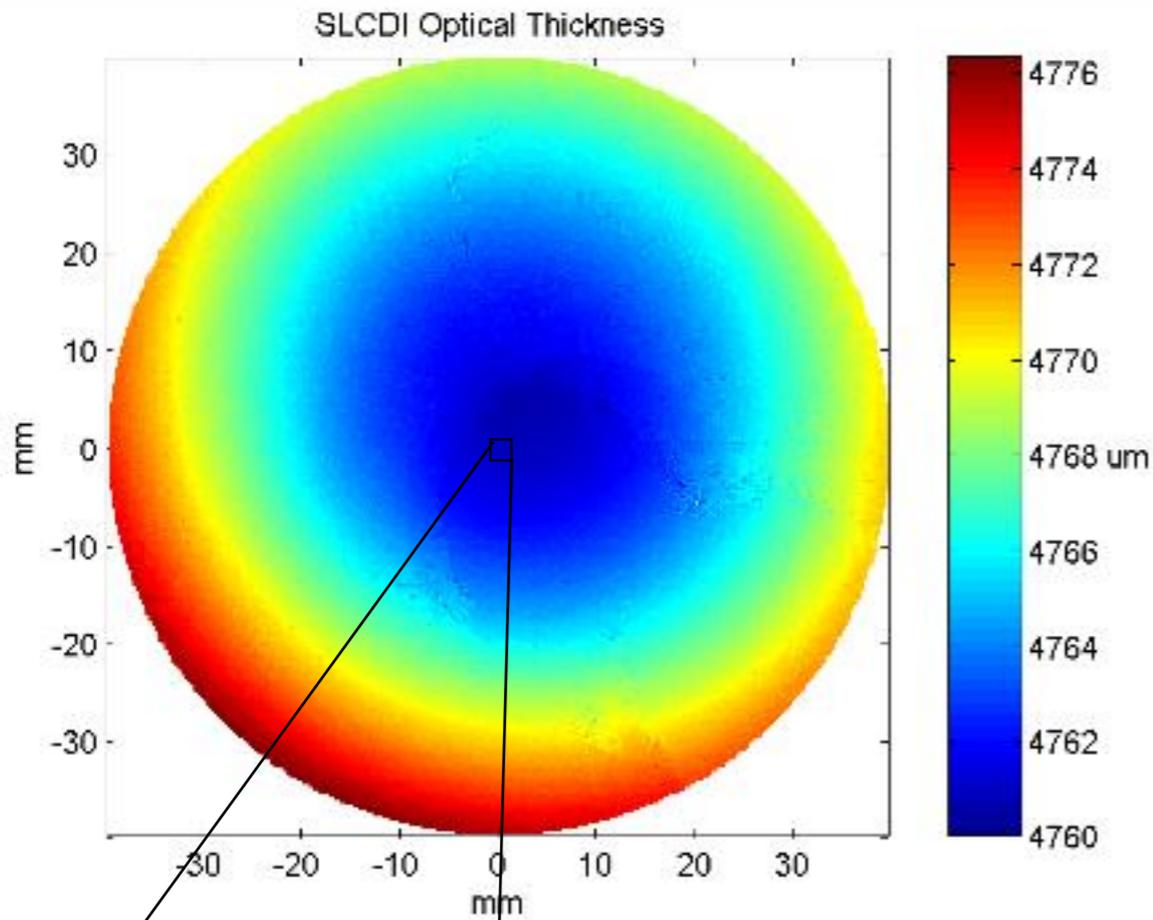
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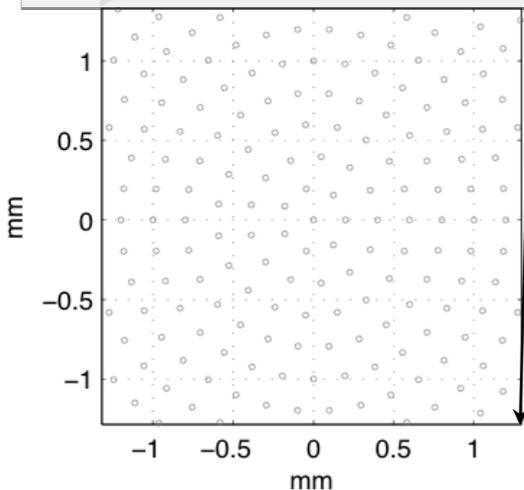
Results:

A 3.5" BK7 domelet was tested using both SLCDI & a Zygo interferometer.

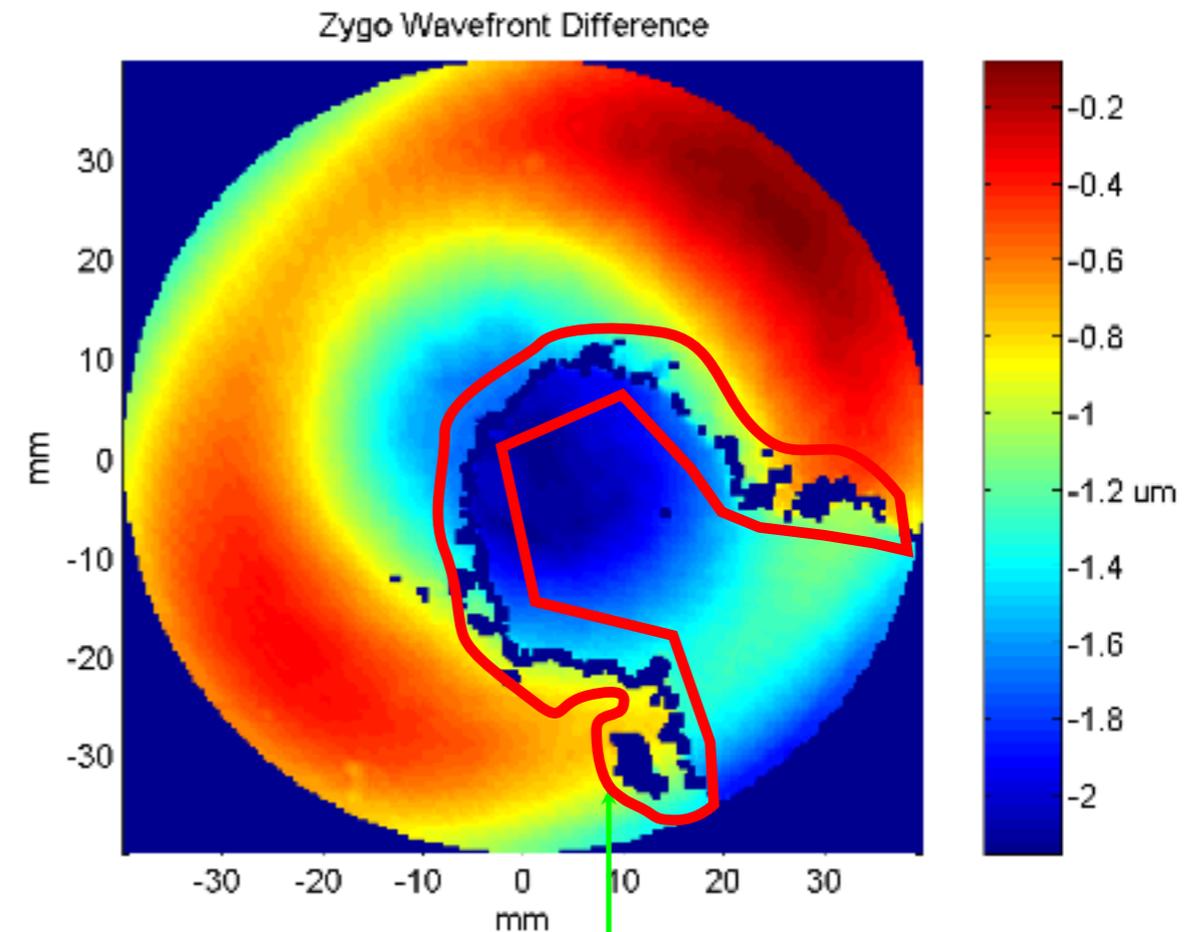
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Sampling Pattern



Sample Separation:
200 μm



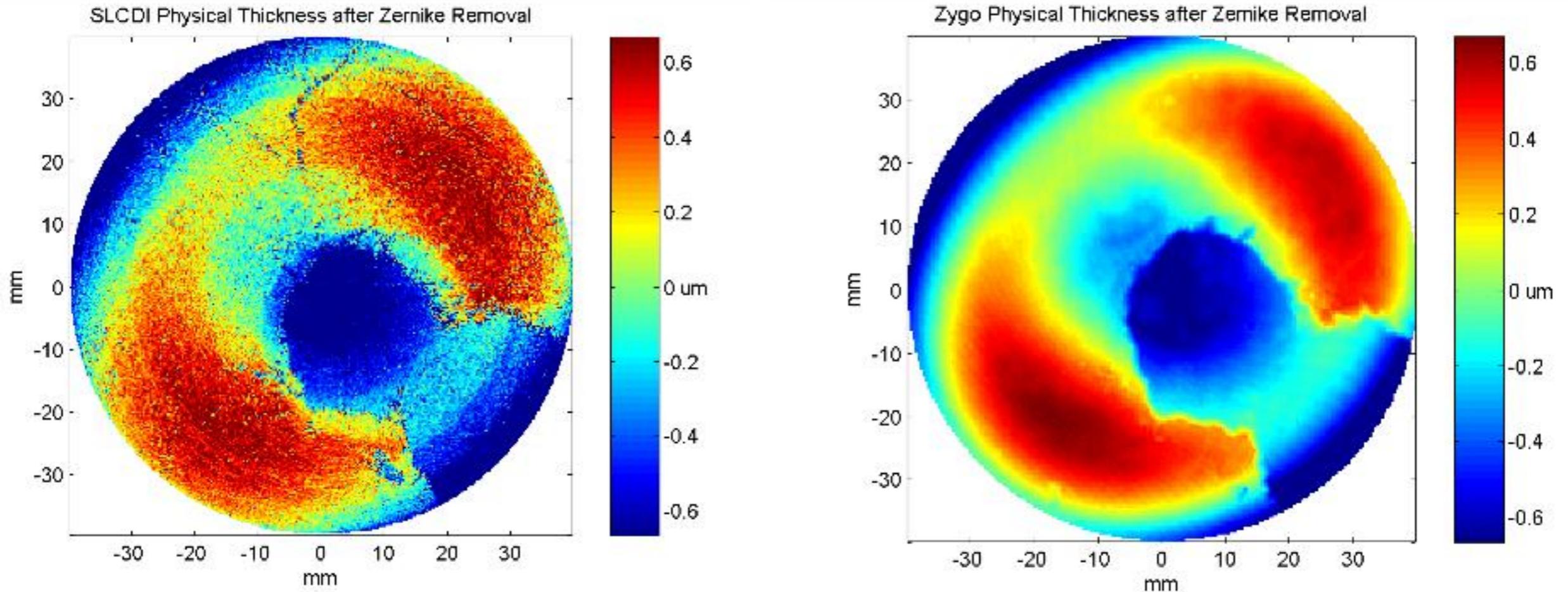
Phase unwrapping fails at discontinuities

Note: The Zygo system is aligned to remove tip/tilt and defocus.

Results:

The images can be compared by converting both maps to physical thickness and remove piston, tip/tilt, and defocus.

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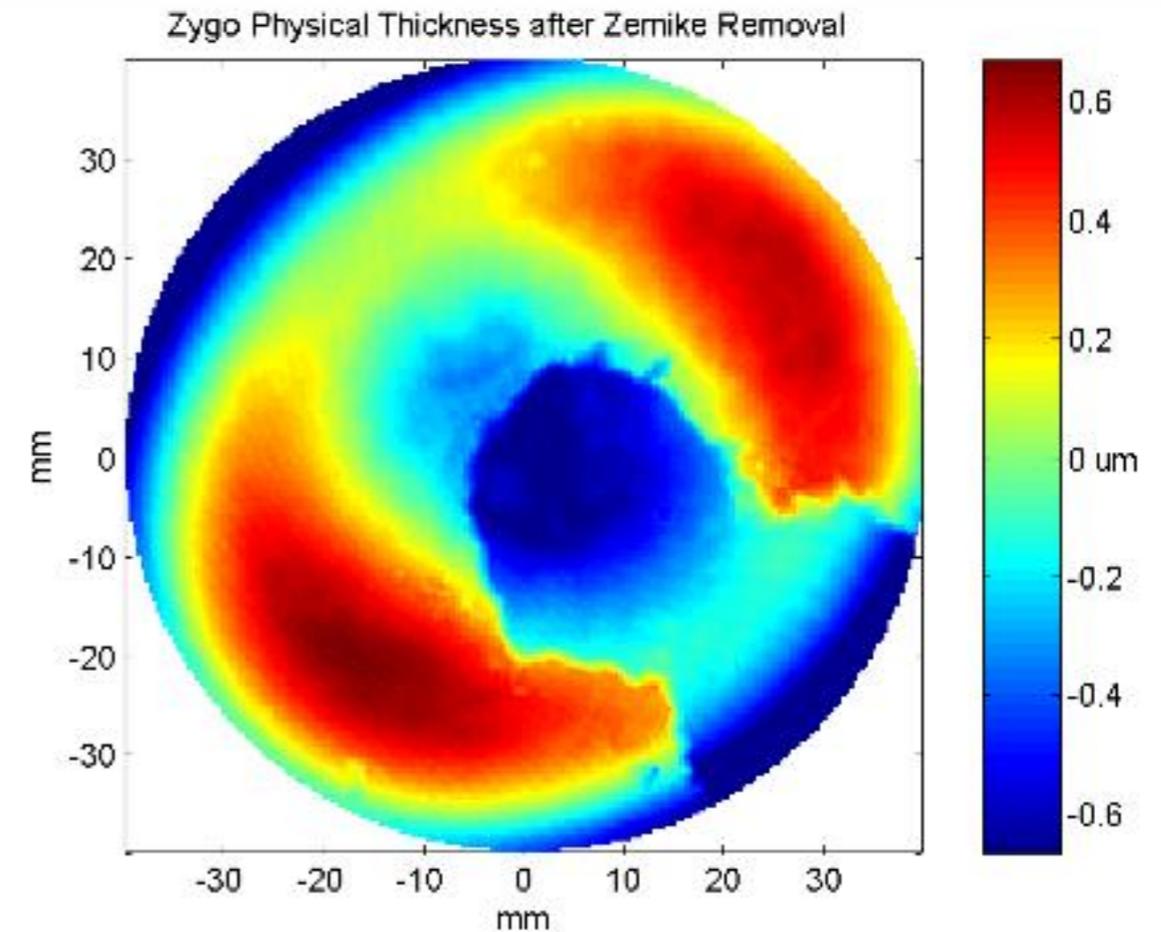
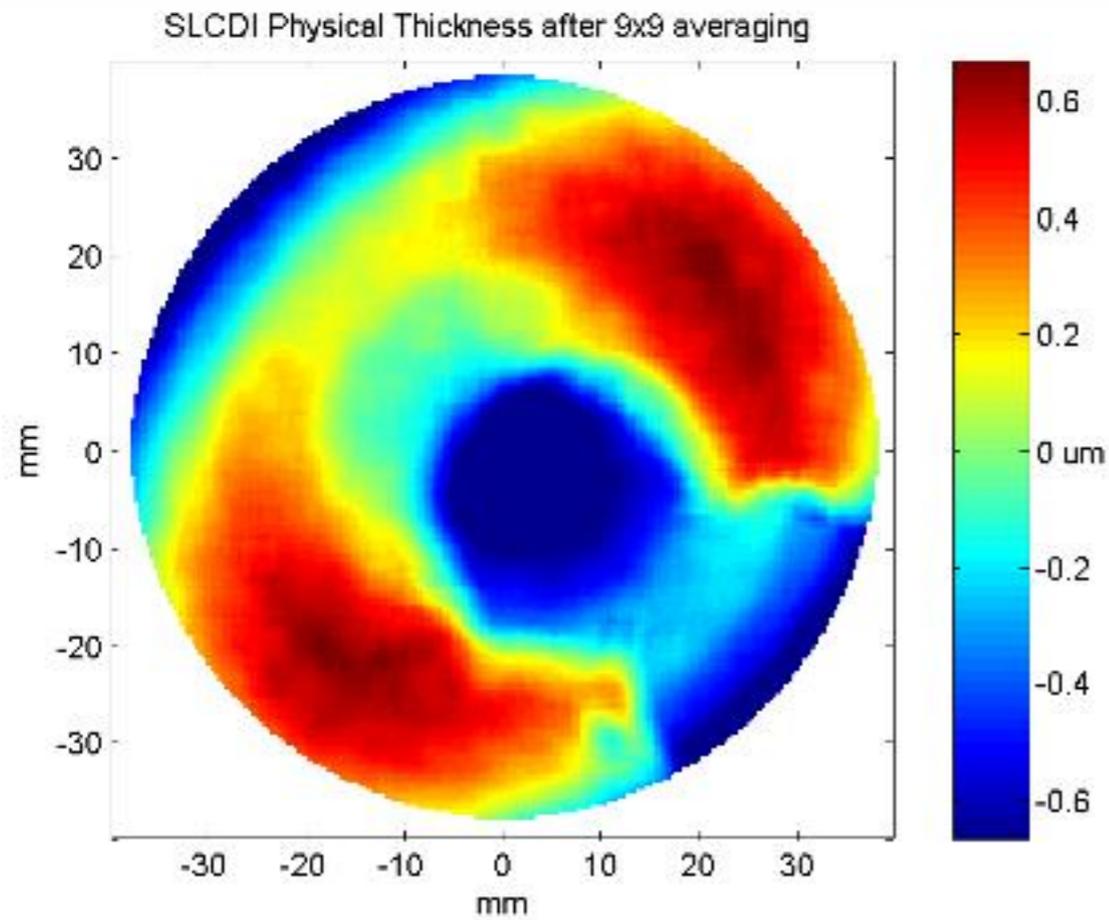


Zernike Order		Fit Coefficients (μm)	
		SLCDI	Zygo
0	Piston	+4811.0	-0.946
1	Tip	-0.4	+0.059
2	Tilt	-0.8	-0.132
3	Defocus	+0.8	+0.284

Results:

Nearest-neighbor averaging reduces the noise in the SLCDI image.

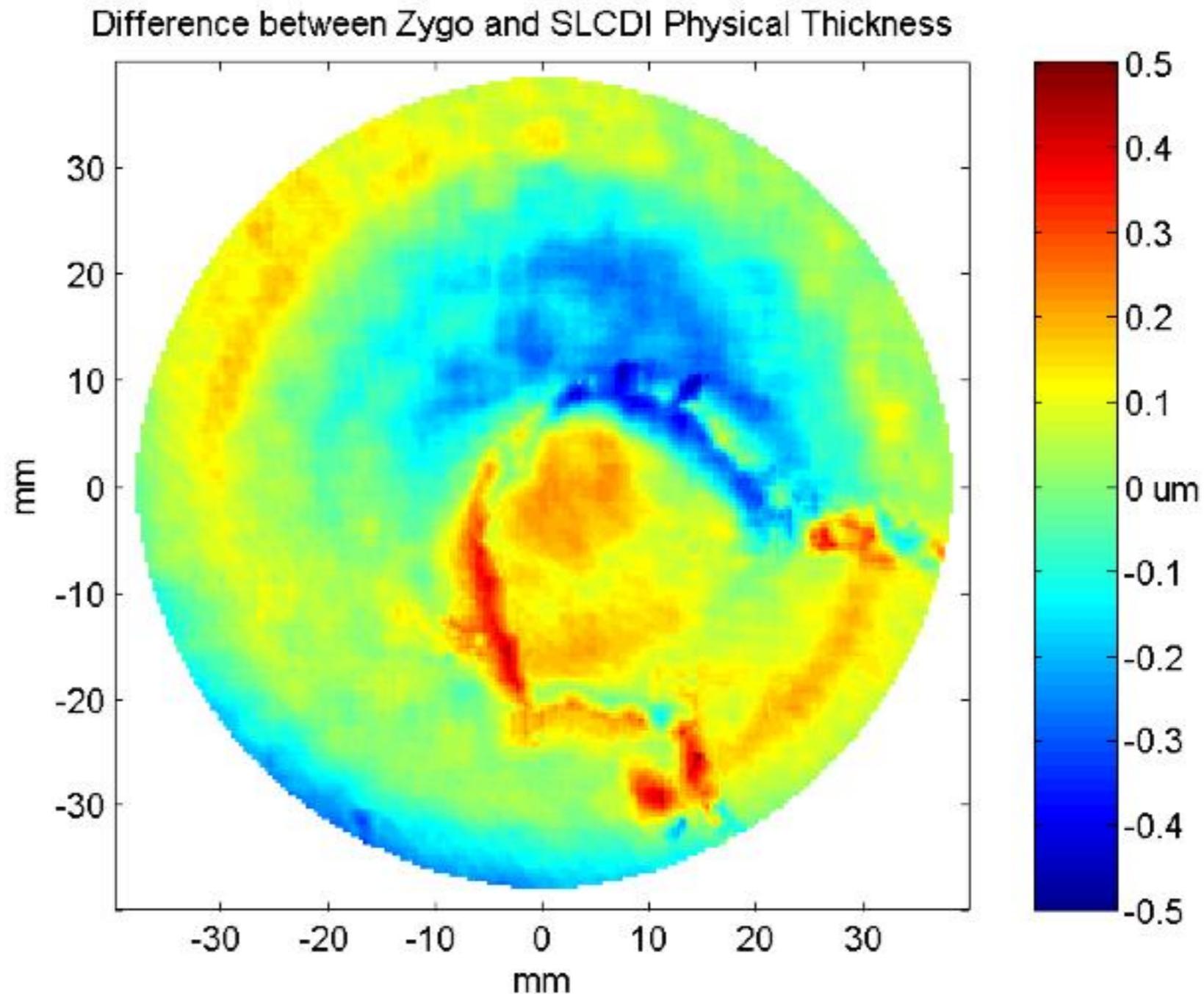
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Results:

The maximum difference between the Zygo and SLCDI data is 200 nm, when disregarding the edge of the coating defect.

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Outline

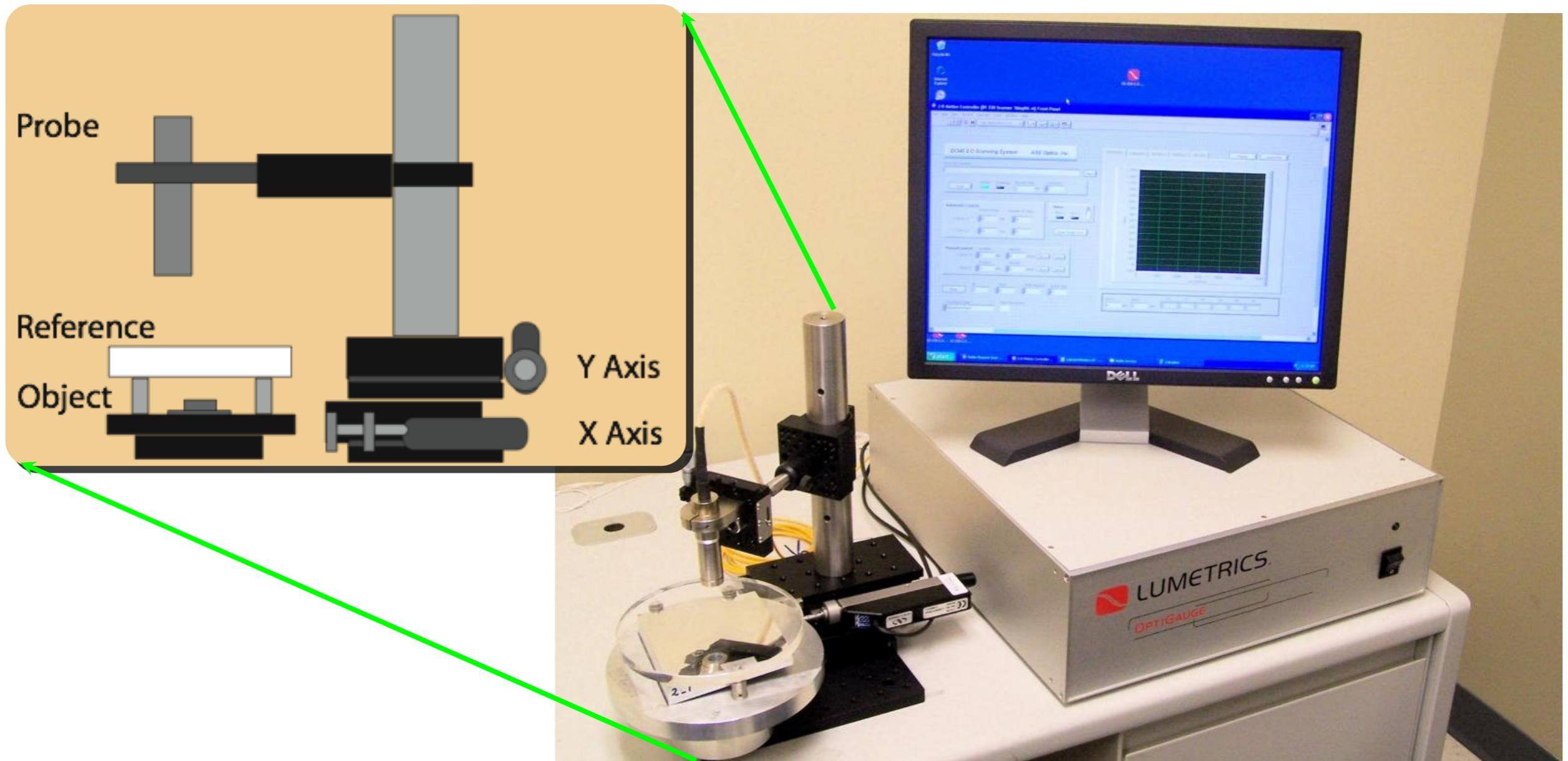
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- Lumetrics DI Overview
- Hemispheric dome scanning (Army SBIR)
- **Aspheric surface scanning (independent research)**

Scanner Components

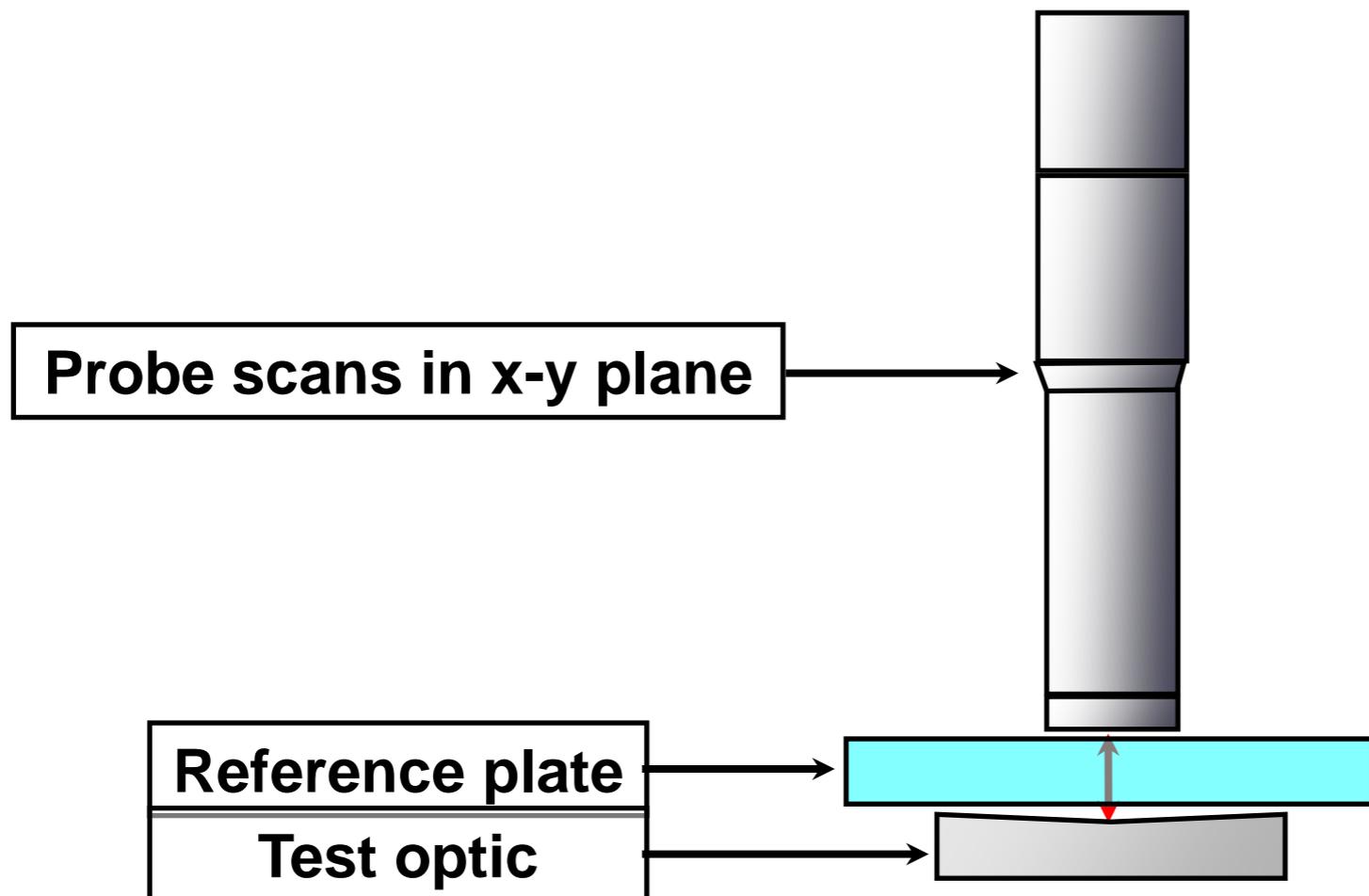
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The scanner incorporates two Newport LTA-HS motorized linear stages with 0.035 μm resolution.

SLCDI measures surface profiles by measuring the airgap between a reference and a test optic.

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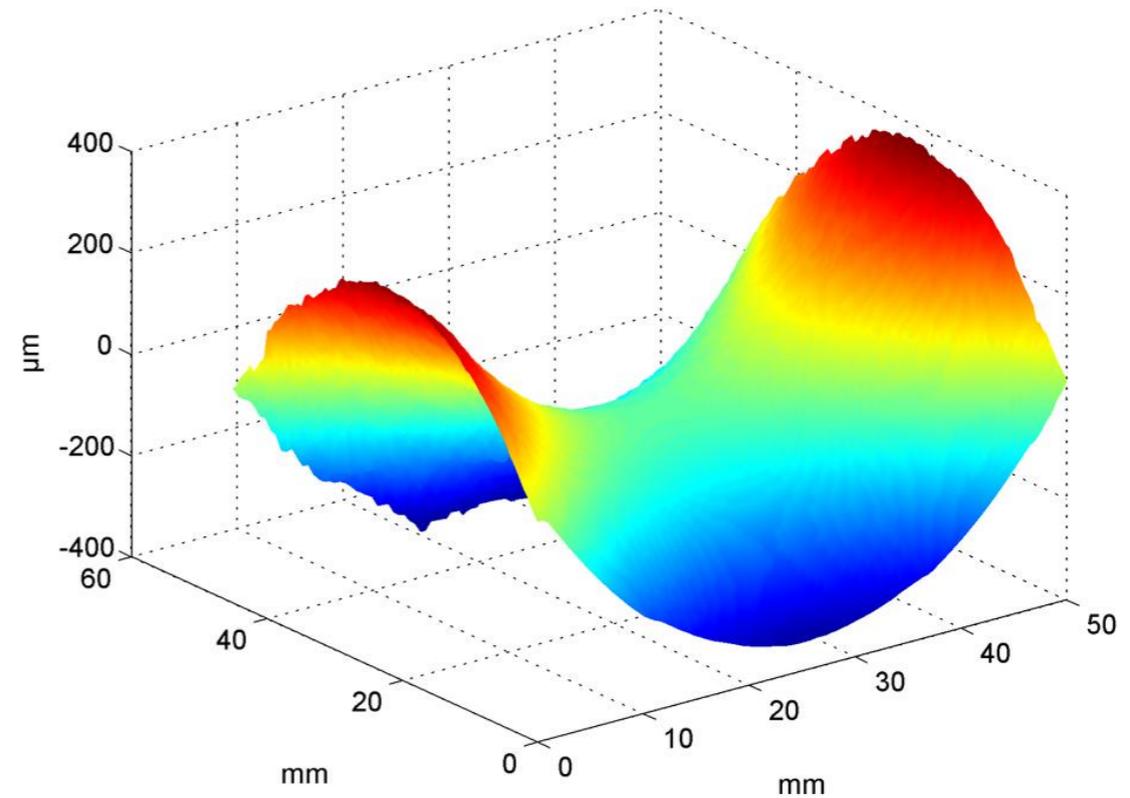
Results:

We measured a 50 mm square portion of a biconic mirror with radii of 799.5 mm and -759.23 mm.

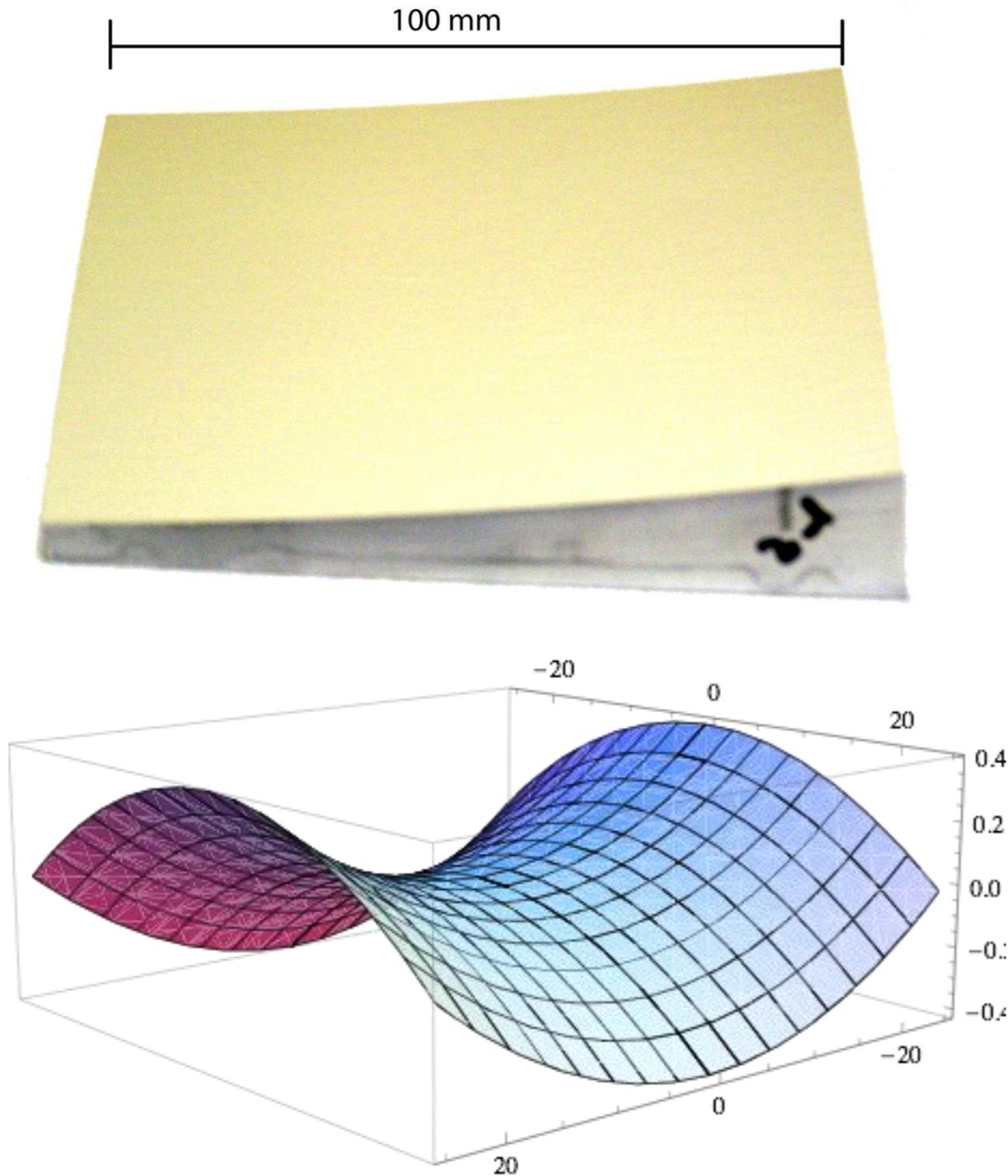
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SLCDI surface profile after removal of tip/tilt



50 μm spatial resolution



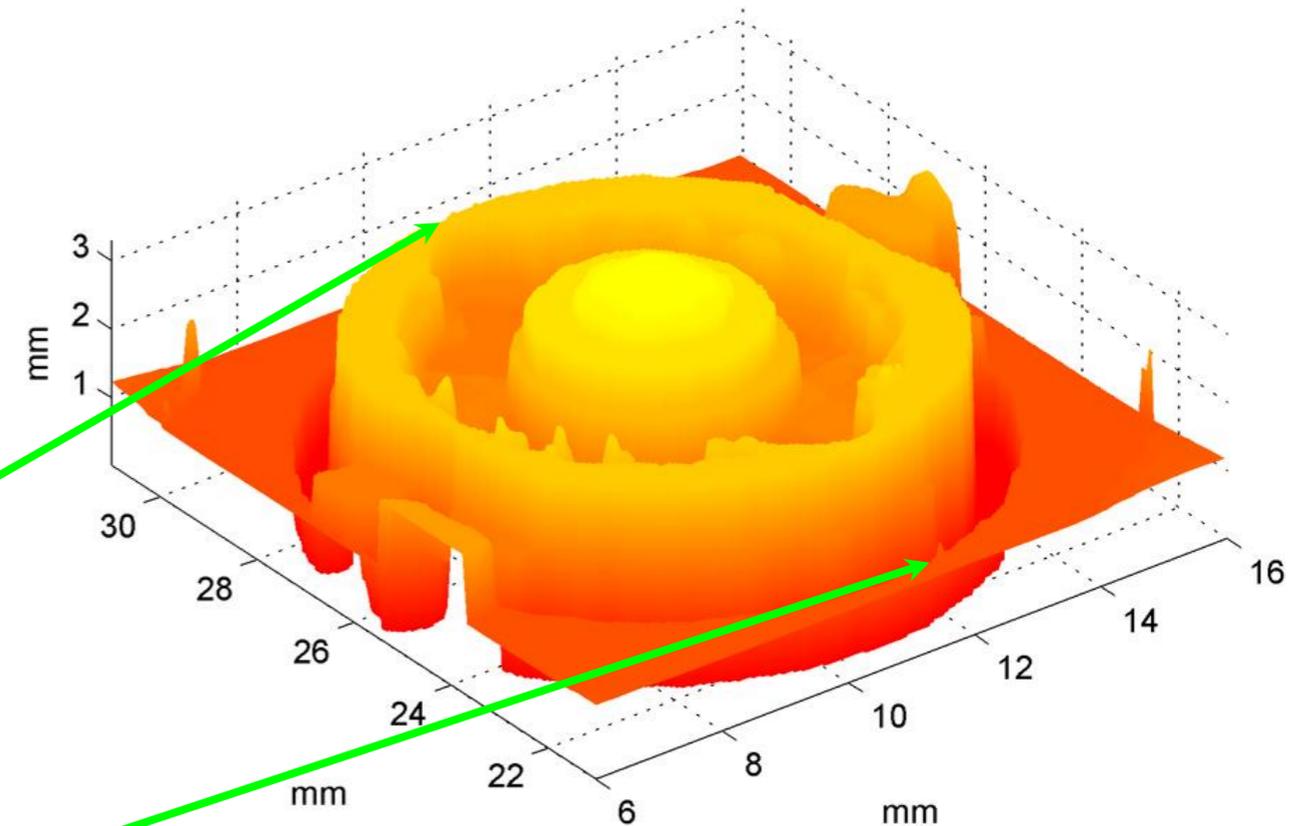
Results:

SLCDI can measure discontinuous surfaces without encountering phase ambiguities.

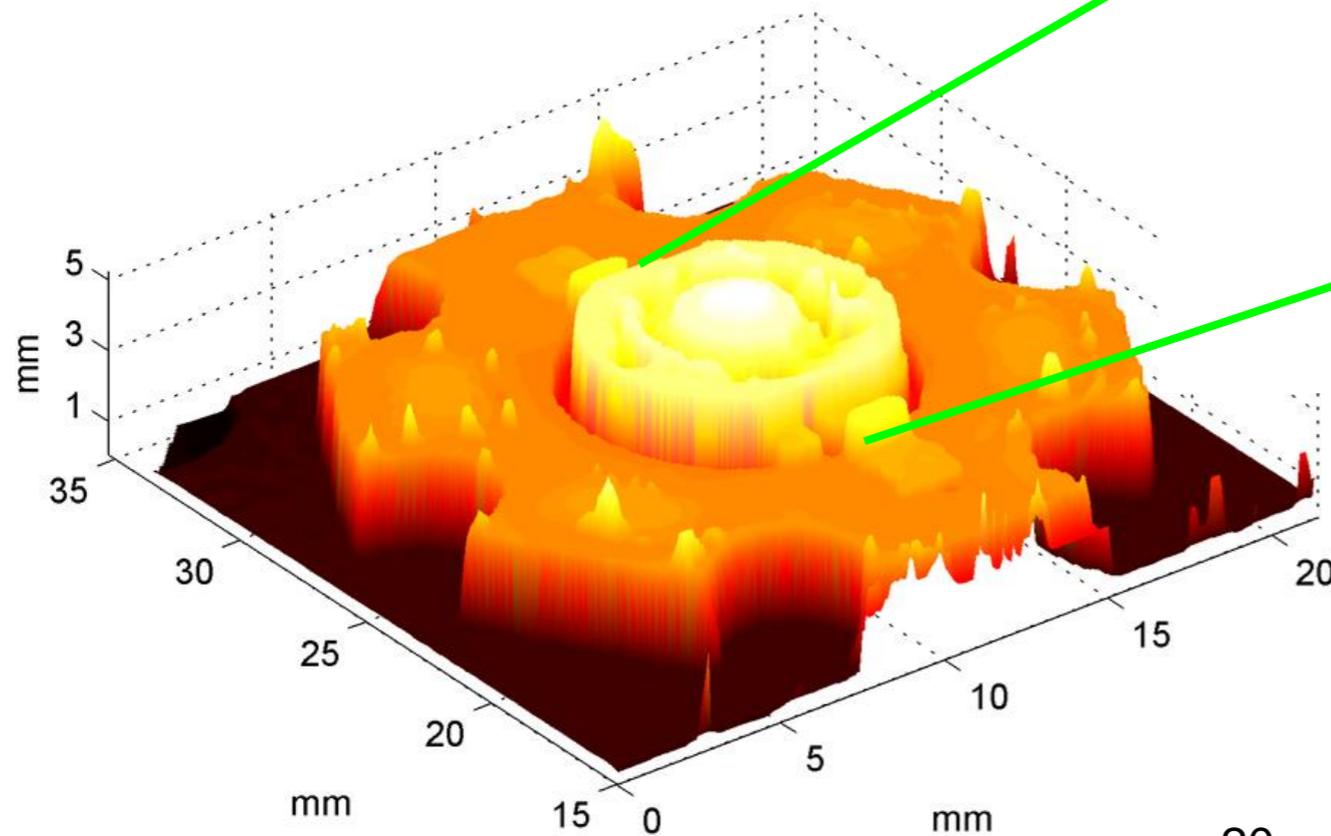
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50 μm spatial resolution



160 μm spatial resolution



Conclusions

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- **SLCDI is a non-contact metrology solution capable of simultaneously measuring both optical thickness and surface profile.**
- **SLCDI yields results that are in agreement with traditional interferometry to within 200 nm.**
- **SLCDI can measure non-traditional shapes, such as saddle mirrors and complex surfaces.**
- **This metrology topic is no longer supported by the US Army. We are seeking new funding sources for this project.**

Backup slides

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All the math...

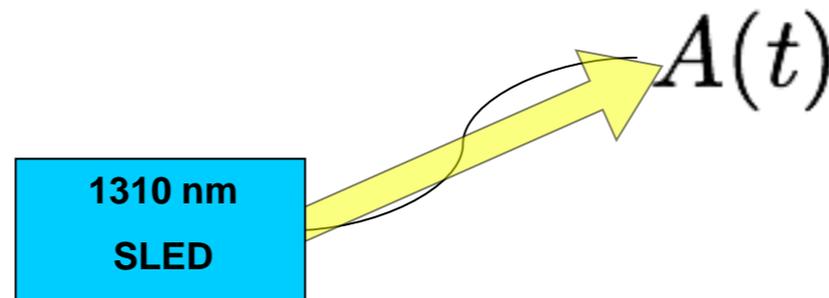
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The Math You Need to Know: Part 1

Autocorrelation

The amplitude of the electric field of the SLED light at a time t is $A(t)$.



The autocorrelation of the field amplitude is the integral of two signals displaced by an increment of time.

$$\Gamma(t, \tau) = \langle A^*(t)A(t + \tau) \rangle = \frac{\int_{-T/2}^{+T/2} A^*(t)A(t + \tau)}{T}$$

For a stationary random process, the autocorrelation is independent of the time, t , i.e.

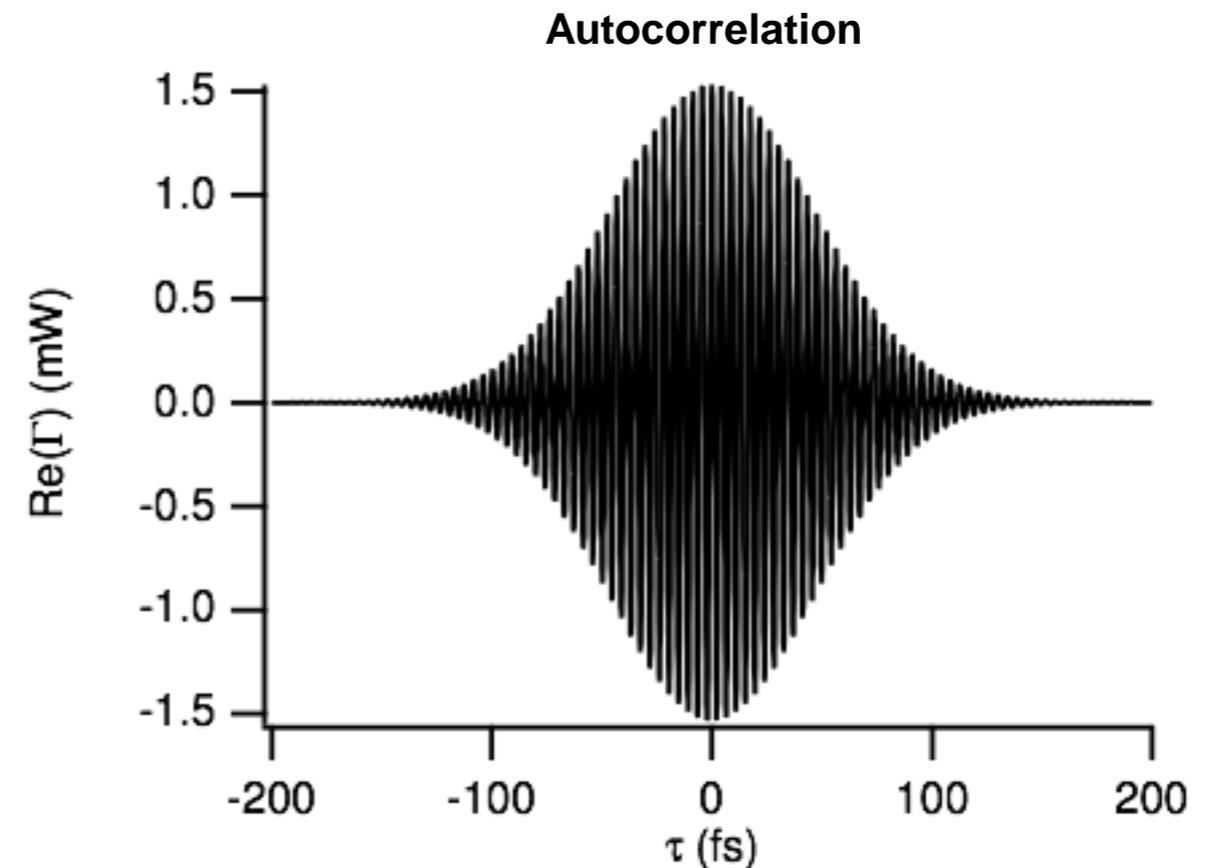
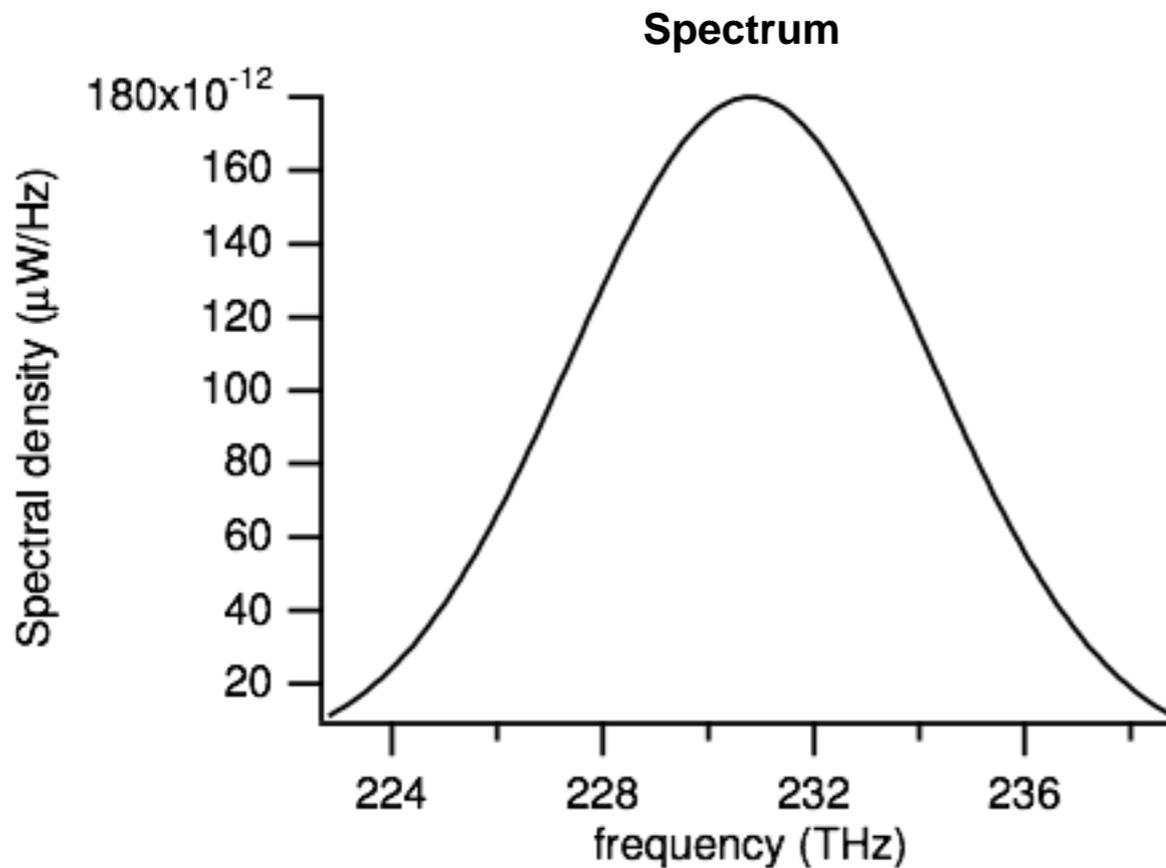
$$\Gamma(t, \tau) = \Gamma(\tau)$$

The Math You Need to Know: Part 2

Wiener-Khintchine Theorem



The autocorrelation is the Fourier transform of the SLED spectrum



$$S(\nu) = a_0 \exp \left[-4 \ln(2) \left(\frac{\nu - \nu_0}{\Delta\nu} \right)^2 \right]$$

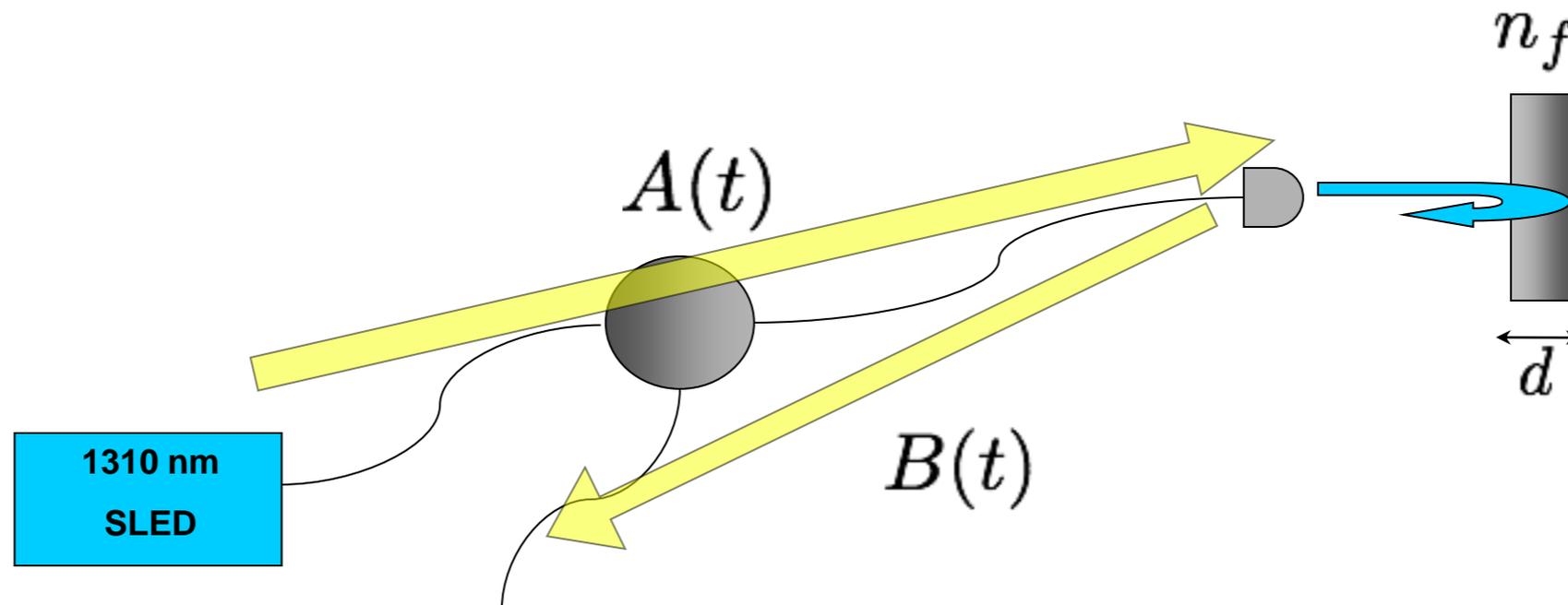
$$\Gamma(\tau) = \int_{-\infty}^{+\infty} S(\nu) \exp(-i 2\pi\nu\tau) d\nu.$$

$$\Gamma(\tau) = a_0 \left| \frac{\Delta\nu}{2} \sqrt{\frac{\pi}{\ln(2)}} \right| \exp \left[- \left(\frac{\pi \Delta\nu}{2\sqrt{\ln(2)}} \tau \right)^2 \right] \exp(-i 2\pi \nu_0 \tau).$$

$$S(\nu) = \int_{-\infty}^{+\infty} \Gamma(\tau) \exp(+i 2\pi\nu\tau) d\tau$$

Theory of Operation: Field Propagation, Pt. 1

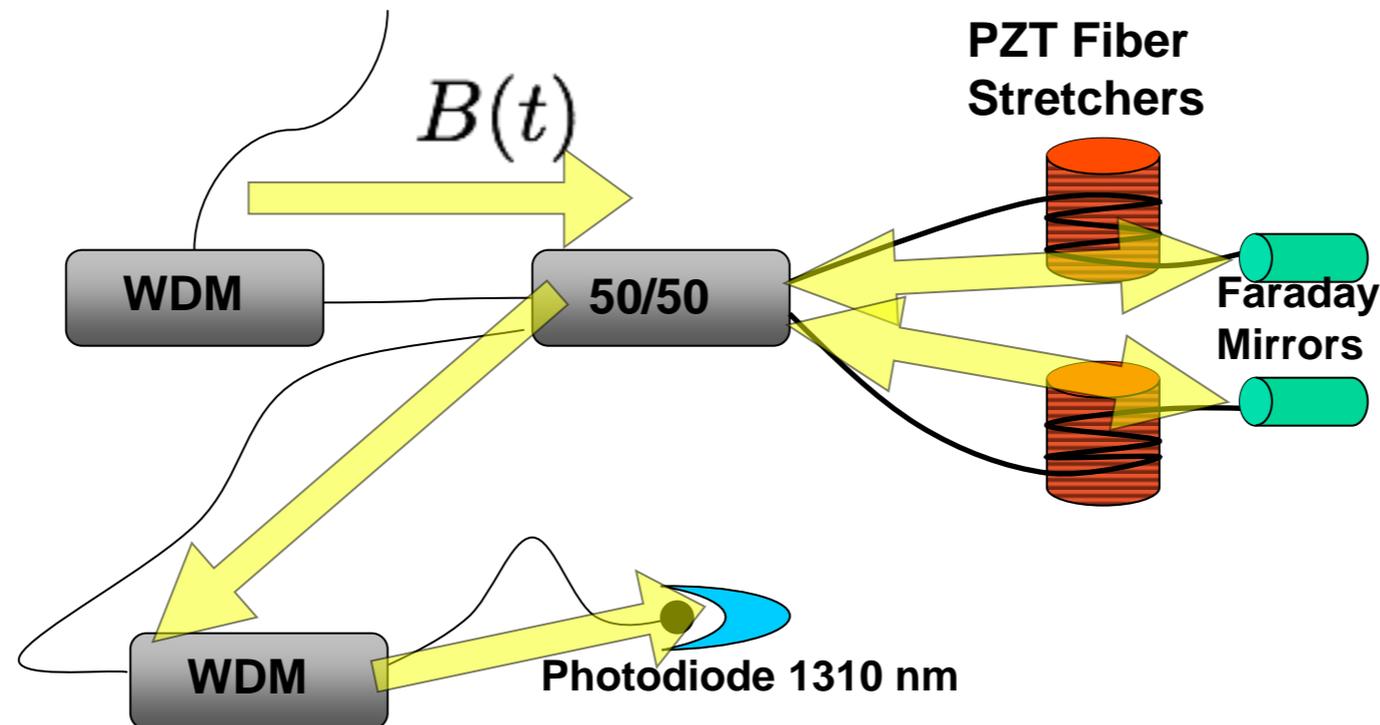
The light collected by the probe is the sum of the fields reflected from each surface.



$$B(t) = r_1 A(t) + r_2 A(t - 2n_f d/c)$$

Theory of Operation: Field Propagation, Pt. 2

The light enters the fiber Michelson interferometer, and each returns a reflection displaced in time. The photodiode reads the intensity of the light.



$$\begin{aligned}
 I(d_1, d_2) &= \langle |B(t + 2n_i d_1/c) + B(t + 2n_i d_2/c)|^2 \rangle \\
 &= \langle [B^*(t + 2n_i d_1/c) + B^*(t + 2n_i d_2/c)] [B(t + 2n_i d_1/c) + B(t + 2n_i d_2/c)] \rangle \\
 &= \langle B^*(t + 2n_i d_1/c)B(t + 2n_i d_1/c) \rangle \dots \\
 &\quad \dots + \langle B^*(t + 2n_i d_1/c)B(t + 2n_i d_2/c) \rangle \dots \\
 &\quad \dots + \langle B^*(t + 2n_i d_2/c)B(t + 2n_i d_1/c) \rangle \dots \\
 &\quad \dots + \langle B^*(t + 2n_i d_2/c)B(t + 2n_i d_2/c) \rangle .
 \end{aligned}$$

Theory of operation: The Meaning, Pt. 1



The intensity expression becomes surprisingly simple when the B terms are expanded in terms of A, and then written as autocorrelations.

$$\begin{aligned}
 I(\tau) = & 4 \operatorname{Re}[r_1^* r_2 \Gamma(-2n_f d/c)] \cdots \\
 & \cdots + 2(|r_1|^2 + |r_2|^2) \{ \Gamma(0) + \operatorname{Re}[\Gamma(\tau)] \} \cdots \\
 & \cdots + 2 \operatorname{Re}[r_1^* r_2 \Gamma(\tau - 2n_f d/c)] \cdots \\
 & \cdots + 2 \operatorname{Re}[r_1 r_2^* \Gamma(\tau + 2n_f d/c)].
 \end{aligned}$$

small constant terms

peak at 0

peak at +2n_fd/c

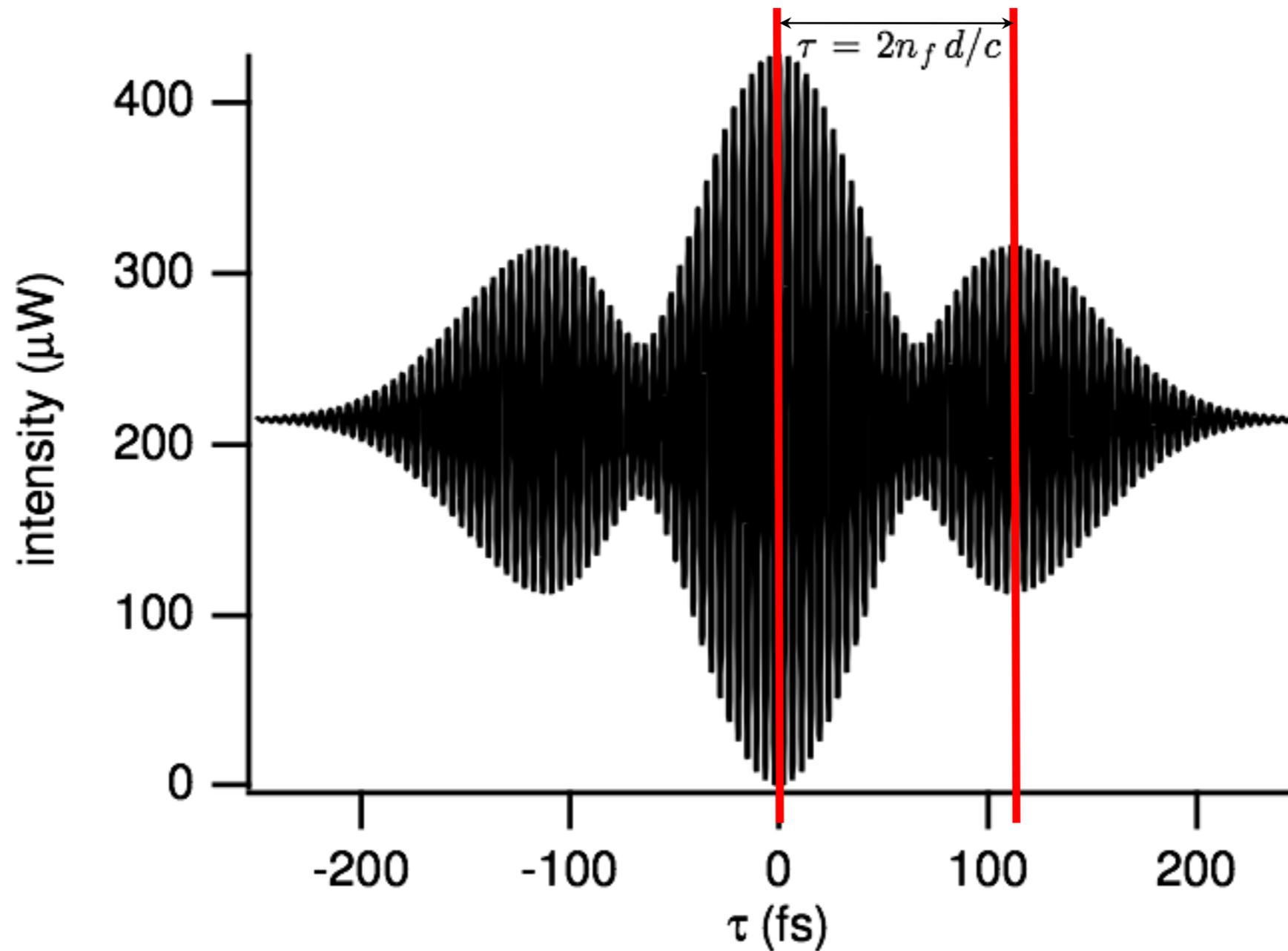
peak at -2n_fd/c

where $\tau = 2(d_2 - d_1)n_i/c,$

Theory of operation: The Meaning, Pt. 2



The distance from the side peak to the center peak is proportional to the optical thickness of the sample.



Scanner Overview:

The scanning software was created in LabVIEW.

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The screenshot displays the Lumetrics DI-330 Dual Interferometer software interface. The main window is titled "Lumetrics DI-330 Dual Interferometer Special for JNJ-A | Version: 2.0.2 (DII: 0) [Fixed Freq]". It features several panels:

- Surf Scanning:** Includes buttons for "Start (new)", "Stop (Cancel)", "Finished (End)", and "Open Diag". A progress indicator shows "Pt 0/10".
- Detailed Surface Data:** Contains a table with columns: Surf., Scans, Mean, Min., Max., Std., Total Optical, Ref. Index, Mat. Thickness, and Total Material. The table shows three surface scans with a mean value of 4577.43 for the first scan and zero for the others.
- ADC Captured Waveform:** A plot showing data versus optical distance in micrometers (um). The y-axis ranges from -500 to 2500, and the x-axis ranges from 0.0 to 6000.0. Two distinct peaks are visible at approximately 1500 and 6000 um.
- DI Dome Scan.vi:** A sub-window with controls for "GPIO Address" (set to 1) and "Angle Inputs" (Resolution: 0.2, Radius: 88.9, Start/Stop angles).
- Triggered Data Status:** A panel with checkboxes for "CTS Level", "Input Triggered", and "Waiting for ADC". It also shows "Sample Number" (48840) and "ADC Mode" (Continuous Run, Com Trigger Run).

The Windows taskbar at the bottom shows the "start" button and several open applications, including "DI Dome Scan.vi", "DI Move to Coordina...", "Measure Wobble.vi", and "3 DI-330-2.0.2-A5...". The system clock indicates the time is 4:49 PM.